

Precision calculation of Higgs plus one jet at NNLO

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Introduction

Higgs boson discovered [Atlas collaboration 2012, CMS collaboration 2012], what next?

- Establish if it is the SM Higgs Boson or something else.
- Investigate its coupling to other SM particles.

This requires a very good theoretical knowledge of the new particles's behaviour, in particular its p_T spectrum.

- Understand how the signal behaves under jet cuts, as are applied for $H \rightarrow WW$ via VBF to supress $t\bar{t}$ background [Atlas collaboration 2012, CMS collaboration 2012].
- Jet substructure techniques to access $H \rightarrow b\bar{b}$ decays [Butterworth, Davison, Rubin, Salam 2008].

Also: better understanding of jet binning in $H \rightarrow WW$.

Where do we stand?

- $H + J$ at NLO in HEFT [De Florian, Grazzini, Kunszt 1999, Ravindran, Smith, Van Neerven 2002, Glosser, Schmidt 2002]
with finite m_t effects [Harlander, Neumann, Ozeren, Wiesemann 2012].
- $gg \rightarrow H + J$ at NNLO in HEFT [Boughezal, Caola, Melnikov, Petriello, Schulze 2013]

We provide a second computation of $gg \rightarrow H + J$ at NNLO in HEFT

- Important crosscheck
 - Distributions in p_T and η
- ☞ One of the first NNLO processes done with two different subtraction formalisms
→ Opportunity for benchmarking

Antenna subtraction

Numerical programs don't like infinities...

$$\begin{aligned} d\hat{\sigma}_{ij,NNLO} = & \int_{d\Phi_{n+2}} [d\hat{\sigma}_{ij,NNLO}^{RR} - d\hat{\sigma}_{ij,NNLO}^S] \\ & + \int_{d\Phi_{n+1}} [d\hat{\sigma}_{ij,NNLO}^{RV} - d\hat{\sigma}_{ij,NNLO}^T] \\ & + \int_{d\Phi_n} [d\hat{\sigma}_{ij,NNLO}^{VV} - d\hat{\sigma}_{ij,NNLO}^U] \end{aligned}$$

[Gehrmann-De Ridder, Gehrmann, Glover 2007, Kosover 1998]

Other formalisms are q_T -subtraction [Catani, Grazzini 2007], Residue subtraction [Frixione, Kunszt, Signer 1996], Sector decomposition [Binoth, Heinrich 2000] and a combination of both [Czakon 2010].

Structure of the subtraction terms at NLO

Real subtraction term includes

$$X_3^0(i,j,k) |M_n^{(0)}(\dots, I, K, \dots)|^2 J_n(\dots, I, K, \dots)$$

Virtual contribution contains

$$\begin{aligned} & \mathcal{X}_3^0(i,j) |M_n^{(0)}(\dots, i, j, \dots)|^2 J_n(\dots, i, j, \dots) \\ & - \int \frac{dz_1}{z_1} \frac{dz_2}{z_2} (\Gamma(z_1) \delta(1-z_2) + (1 \leftrightarrow 2)) |M_n^{(0)}(z_1 p_1, z_2 p_2, \dots)|^2 J_n(\dots) \end{aligned}$$

where

- X_3^0 (\mathcal{X}_3^0) are the unintegrated (integrated) 3-parton 0-loop antenna functions.
- The mapping $(i, j, k) \rightarrow (I, K)$ interpolates between singular limits.
- J_n is the measurement function selecting n jets.
- Γ is the mass factorisation kernel.

Structure of the subtraction terms at NLO

Recently, progress has been achieved in understanding the structure of the integrated subtraction terms [Currie, Glover, Wells 2013]:

$$\mathcal{X}_3^0(I, J) = \mathcal{J}_2^{(1)}(I, J)$$

$$\mathcal{X}_3^0(1, I) + \Gamma(z_1) = \mathcal{J}_2^{(1)}(1, I)$$

$$\mathcal{X}_3^0(1, 2) + \Gamma(z_1)\delta(1 - z_2) + \Gamma(z_2)\delta(1 - z_1) = \mathcal{J}_2^{(1)}(1, 2)$$

and $\mathcal{J}_2^{(1)}(I, J) = \mathcal{I}_2^{(1)}(I, J) + \text{Finite}$,

where $\mathcal{I}_2^{(1)}(I, J)$ is catani's IR singularity operator. This correspondence might allow an automatisation of NNLO subtraction starting from the known IR behaviour of loop amplitudes!

Additional features at NNLO

At RR:

- $X_3^0(i, j, k)|M_{n+1}^{(0)}(\dots, I, K, \dots)|^2 J_{n+1}(\dots, I, K, \dots)$
- $X_4^0(i, j, k, \ell)|M_n^{(0)}(\dots, I, L, \dots)|^2 J_n(\dots, I, L, \dots)$
- $X_3^0(i, j, k)X_3^0(I, K, \ell)|M_n^{(0)}(\dots, \mathbf{I}, \mathbf{L}, \dots)|^2 J_n(\dots, \mathbf{I}, \mathbf{L}, \dots)$

At RV:

- $\mathcal{J}^{(1)}(i, j)|M_{n+1}^{(0)}(\dots, i, j, \dots)|^2 J_{n+1}(\dots, i, j, \dots)$
- $X_3^0(i, j, k)|M_n^{(1)}(\dots, I, K, \dots)|^2 J_n(\dots, I, K, \dots)$
- $X_3^1(i, j, k)|M_n^{(0)}(\dots, I, K, \dots)|^2 J_n(\dots, I, K, \dots)$

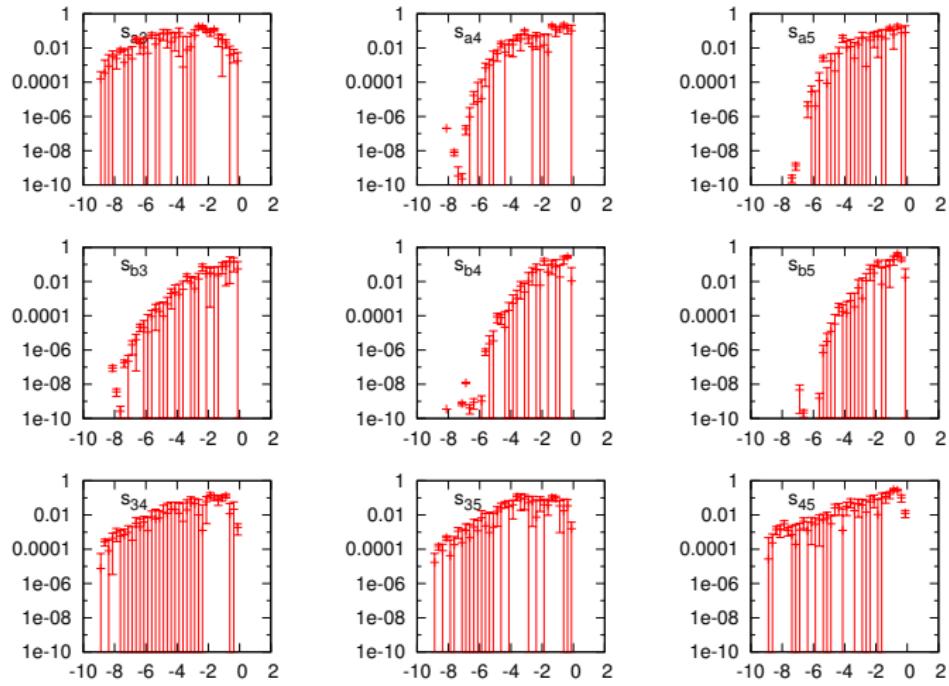
At VV:

- $\mathcal{J}^{(2)}(i, j)|M_n^{(0)}(\dots, i, j, \dots)|^2 J_n(\dots, i, j, \dots)$
- $\mathcal{J}^{(1)}(i, j)|M_n^{(1)}(\dots, i, j, \dots)M_n^{(0)}(\dots, i, j, \dots)^\dagger|J_n(\dots, i, j, \dots)$
- $\mathcal{J}^{(1)}(i, j)^2|M_n^{(0)}(\dots, i, j, \dots)|^2 J_n(\dots, i, j, \dots)$

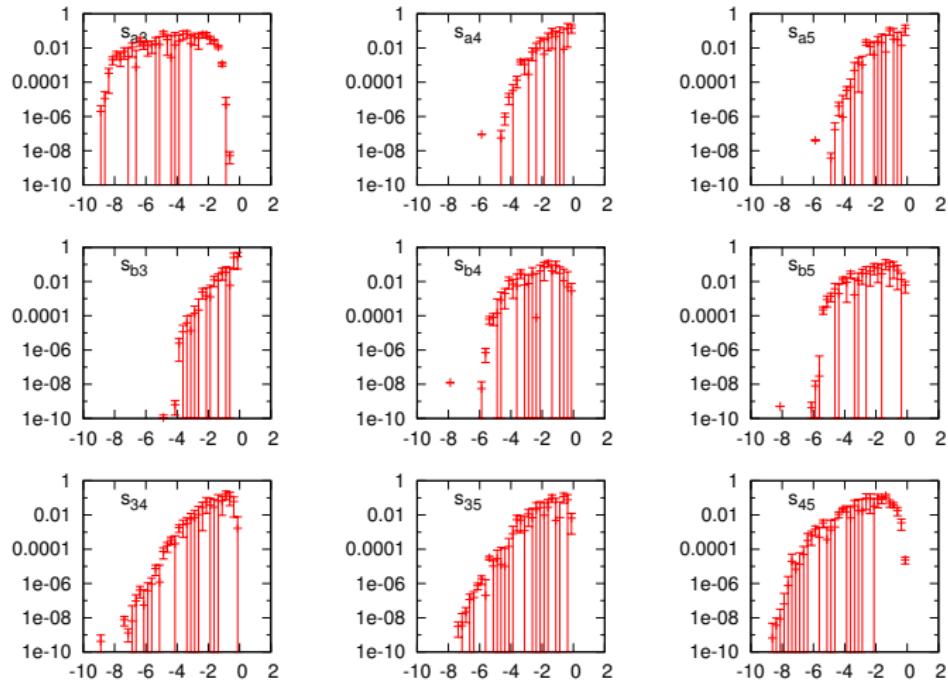
Technicalities

- Computation for 8TeV LHC
- Gluons only
- VEGAS integration coded up in FORTRAN
- Dedicated Phase-space generator
 - Split in wedges containing only double single collinear or triple collinear limits.
 - 4 rotations per PS point to cancel spurious angular terms in collinear limits.
- Anti- k_T with $R=0.5$, p_T cut at 30GeV
- Use NNPDF23 set

Performance of the subtraction terms (wedge A)



Performance of the subtraction terms (wedge B)



Distribution of subtracted RRB weight versus partonic phase-space variables

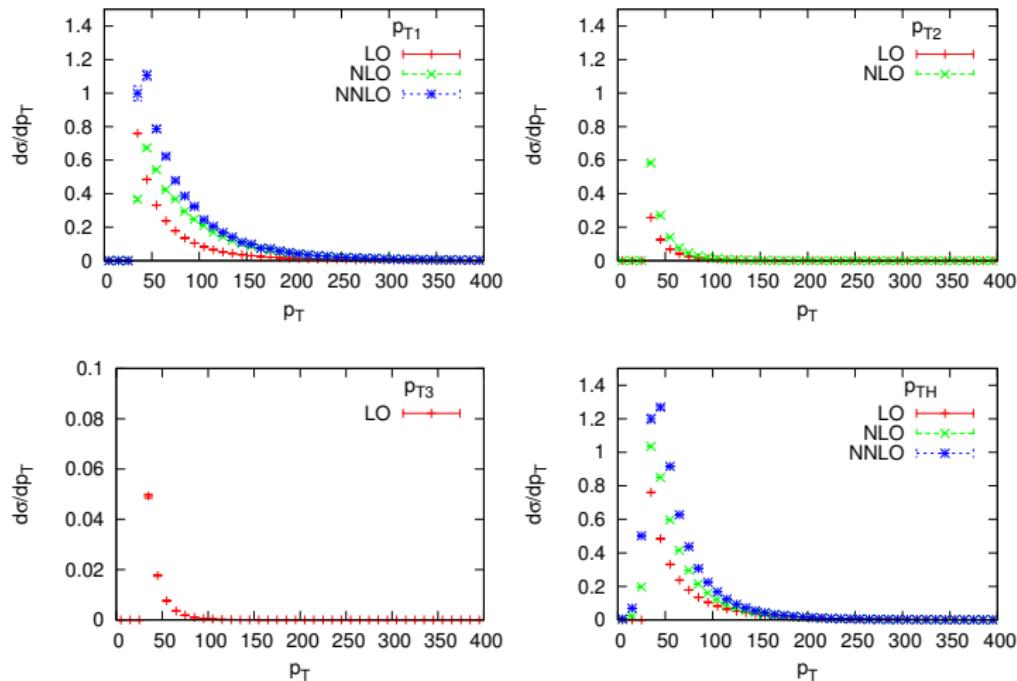
Result

channel	cross section [pb]	approx. processor time
tree	1.9424 ± 0.0004	$\sim 10\text{min}$
virt	2.8857 ± 0.0003	$\sim 40\text{min}$
real	-0.5698 ± 0.0004	$<4\text{h}$
VV	3.1032 ± 0.0010	$\sim 10\text{min}$
RV	-1.1616 ± 0.0077	$<350\text{h}$
RRA	0.1069 ± 0.0339	$<350\text{h} + \sim 5\text{ days warmup (1 core)}$
RRB	0.0488 ± 0.0237	$<300\text{h} + \sim 5\text{ days warmup (1 core)}$

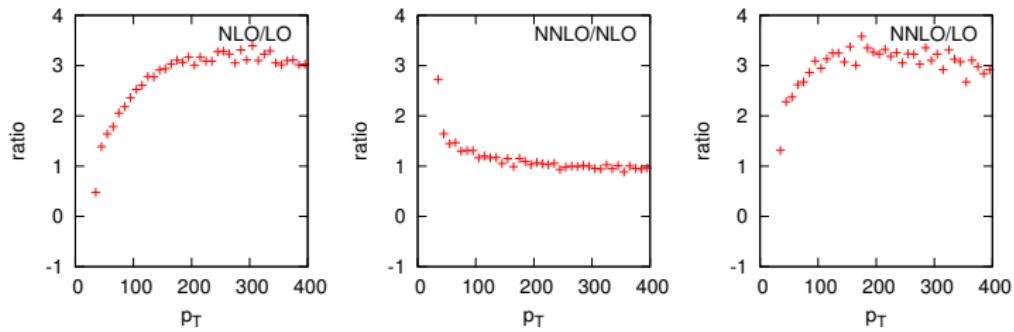
$$\Rightarrow \sigma_{Tot, NNLO} = 6.3557^{+0.1792}_{-0.4702} \text{ pb},$$

with theoretical error from scale variation ($\mu_R = \mu_F = \frac{m_H}{2}, m_H, 2m_H$).

p_T Distributions

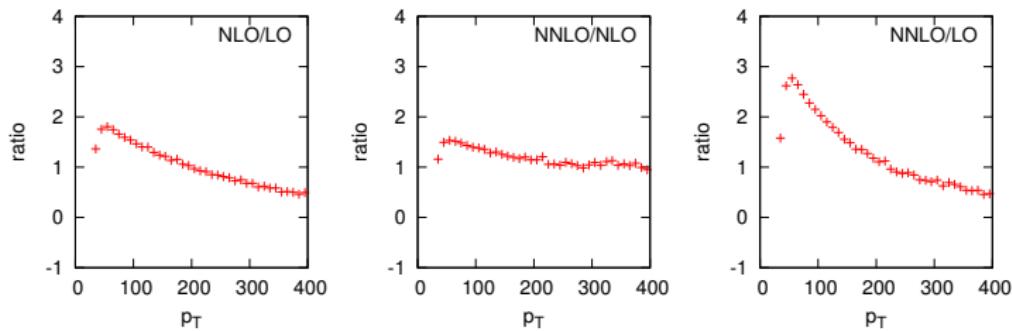


p_T Distributions



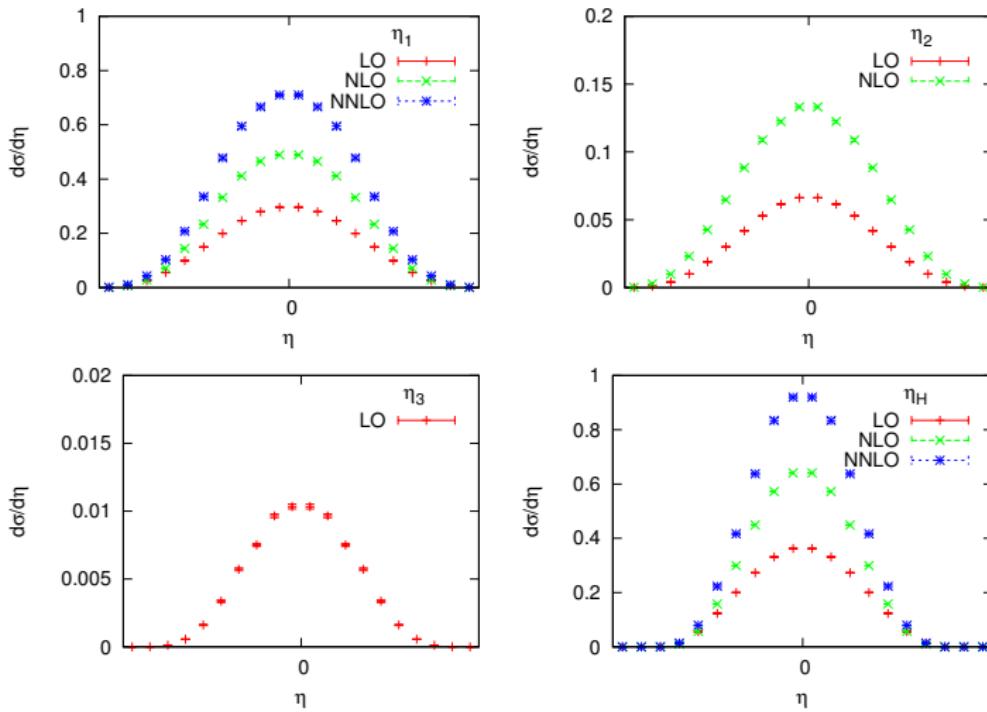
Ratios of the p_T distributions of the first jet

p_T Distributions



Ratios of the p_T distributions of the Higgs boson

η Distributions



Conclusions and outlook

- We presented a computation of $gg \rightarrow H + J$ at NNLO QCD in HEFT.
- The handling of IR divergences is successfully carried out by the antenna subtraction formalism.
- We achieve agreement with existing results and provide distributions in p_T and η of the Higgs boson and jets.
- The next step(s) consist in evaluating the remaining qg and $q\bar{q}$ channels to obtain full results.

Thanks!